LIFE PREDICTION FOR Al IN THE MICROCRACK REGIME USING SAW NDE

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ABSTRACT

Harmonic generation of surface acoustic waves (SAW) is a useful tool for studying surface microcrack initiation during fatigue of high strength aluminum alloys. We have developed a model which relates the length and density of such microcracks, initiated during fatigue, with SAW harmonic generation signals. It was found that the resulting quantitative relationship between the acoustic data and the remaining fatigue life is accurate to within 5% over the last 50% of the fatigue life, spent in the microcrack initiation phase. Extensive tests are now underway to study the general applicability of these concepts to a wide range of high-strength Al alloys. Furthermore, we have started to separate the various contributions to harmonic generation from microcracks that are smaller than the average grain diameter, from those that have been able to grow out of the grain of their origin. These considerations are important in that they (1) provide detailed insight into the process of fatigue damage and (2) may improve our remaining life prediction capability, particularly during the first 90% of the total fatigue life. This concept seems to have applicability to the "Retirement for Cause" program of the Air Force.

INTRODUCTION

The objective of the present work is to establish a procedure for the prediction of the remaining life of an originally smooth, unflawed metallic component. Extensive scanning electron microscopy (SEM) studies on certain aluminum alloys have shown[1-6] that the presence of intrinsic defects in the material such as brittle intermetallic inclusions, will lead to the nucleation of microcracks during fatigue of these alloys. After nucleation the microcracks grow into the matrix, interact with the grain boundaries, and eventually coalesce with other microcracks to form a macrocrack whose subsequent growth will finally terminate the life of the specimen, as discussed extensively by Morris and James in this volume. Furthermore, it has already been shown that simple analytical models of crack nucleation, early crack growth and coalescence in aluminum alloys are able to describe the fatigue failure process, yielding mean and scatter of the life even as the mean grain diameter of the alloy is changed.[7,8] These models, which are the basis for a Monte Carlo simulation, relate the probability of nucleation and rate of early crack propagation to the alloy microstructure in the vicinity of an initiation site. Further studies are underway to improve these models.

Such knowledge of the development of fatigue damage is one necessary input for a successful life prediction, prior to the formation of the macrocrack. The monitoring of this damage, using a nondestructive testing method, forms the other input. Present day, standard nondestructive testing methods are, in general, not sensitive enough to detect such microscopic damage before the ultimate macrocrack is formed. Therefore, and in parallel to the above investigations on the microscopic events leading to ultimate failure, evaluations on new nondestructive testing methods capable of monitoring these microscopic events have been performed.[9] One of these methods, the generation of harmonics in surface acoustic waves, has been extensively studied and was found to be sensitive to microcracks developed during fatigue.[10-12] In the following a tentative relation between the harmonic generation and microcracking parameters is suggested and tested, leading to a semi-quantitative prediction of the remaining life for a high-strength aluminum alloy. At the present time it is believed that the remaining life prediction is accurate to within 5% over the last 50% of the total fatigue life, starting with a smooth bar specimen. This is certainly an improvement over present day fatigue life prediction capabilities, which can only be applied after the formation of the macrocrack. Since the critical flaw sizes in metals may be quite small[9] (low fracture toughness materials) the present results suggest that harmonic generation may be a useful tool for early crack detection and that the suggested procedures may be applicable to programs such as the "Retirement For Cause" program of the Air Force.

BACKGROUND

The generation of second harmonics by surface acoustic waves during fatigue of a high strength aluminum alloy has recently been reported.[10-12] The enhanced generation of a second harmonic with fatigue is attributed to an increased anelasticity of the surface due to development of surface microcracks. Considering a surface crack as an unbonded interface, a possible mechanism for this generation is the distortion that the fundamental surface wave experiences as it propagates across the unbonded interface. The effect was predicted by Richardson[13] who calculated the harmonic amplitude generated by the opening and closing of an unbonded interface between two semi-infinite solid materials for the particular case of an incident plane, longitudinal bulk wave. These calculations indicate that the harmonic generation efficiency depends strongly on the external applied stress, and that under optimum conditions (close to zero applied stress) the second harmonic amplitude is larger than 17% of the fundamental, exceeding by far all generation from other nonlinear sources, such as lattice anharmonicity[14] or dislocation.[15] It is believed at the present time, that similar considerations are applicable to the harmonic generation of surface waves, as will be discussed in the following.

The experimental set-up to determine harmonic generation in surface waves as a function of fatigue was extensively discussed in Ref. 12. Briefly, a fundamental SAW (5 MHz) was transmitted across the gauge section of cantilever beam specimens (Al 7075-T6) that were fatigued in flexure. The tapered geometry generates a uniform surface stress and thus a fairly homogeneous density of microcracks (however note that the through-the-thickness stress distribution is non-uniform).

The amplitude of the second harmonic (10 MHz) was measured at several increments of fatigue. This second harmonic signal is at a maximum close to zero surface stress (the specimen being under static load during the measurement) and this maximum increases with expended fatigue life, consistent with the formation of microcracks during fatigue. A summary of these results[12] is shown in Fig. 1,

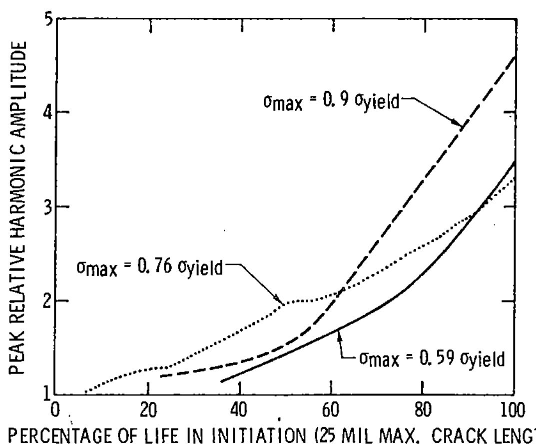

Fig. 1. Harmonic generation as a function of percentage of life in initiation for three different cyclic stress amplitudes (Ref. 12).

in which the change of the peak value of the second harmonic is given as a function of the fraction of expended life in the initiation phase of fatigue, which is here defined as that part of the total life necessary to produce the first large microcrack having a length of approximately 500 μm. Actual total numbers of fatigue cycles applied to each specimen are given in Table I. The curves presented are basically "raw" data since a portion of the second harmonic generation is obscured by the changes in attenuation the SAW experiences due to scattering at the microcracks. In order to unfold these competing effects, a simple analysis has been made taking attenuation

TABLE I

Total number of fatigue cycles applied to produce a longest microcrack of 500 μm.

Stress Level	Fatigue Cycles
$0.59\sigma_{yield}$	22,000
$0.76\sigma_{yield}$	8,000
$0.9\sigma_{yield}$	2,500

effects into account.[12] Assume that the fundamental is attenuated according to

$$A_1(x) = A_1(o)e^{-\alpha_1 x} \tag{1}$$

where $A_1(o)$ is the (constant) fundamental amplitude generated by the transmitter. α_1 is the attenuation coefficient of the fundamental and x the propagation distance away from the transmitter. Between x and x $+\Delta x$ the incremental second harmonic generation would be[12]

$$\Delta A_2(x) = \beta[A_1(x)]^n e^{-\alpha_2 x\ (\ell - x)} \Delta x \tag{2}$$

with β being a coefficient of second harmonic generation efficiency, α_2 the attenuation of the second harmonic and n the power relationship between the second harmonic and the fundamental amplitude. Integration over the total pathlength, ℓ, yields the received second harmonic amplitude

$$A_2(\ell) = \frac{\beta[A_1(o)]^n e^{-\alpha_2 \ell}}{(n\alpha_1 - \alpha_2)} \tag{3}$$

$$[1-e^{-(n\alpha_1-\alpha_2)\ell}] + \text{const},$$

in which the integration constant is determined by the second harmonic contributions from the lattice anharmonicity and dislocation harmonic generation. In previous work[12] it was observed that the effects of attenuation are appreciable only if the interrogated surface of specimen is under tension or, in other works, if the cracks are fully open. The present work is concerned only with the development of the maximum in harmonic generation, which occurs close to zero surface stress (see Fig. 1). Therefore both α_1 and α_2 will be neglected in the following discussion. Furthermore the harmonic generation data will be normalized to the value obtained prior to fatigue, so that the integration constant in Eqn. (3) is equal to 1. Under these simplified conditions

$$A_2(\ell)-1 = \beta\ell[A_1(o)]^n \tag{4}$$

The second harmonic generation coefficient β is the quantity that is related to the microcracking parameters, important to a successful fatigue life prediction.

Such microcracking parameters have been obtained from each of the specimens interrogated, using SEM and in some cases, using optical microscopy. Since most of the cracks are partially closed, it was necessary to load the specimen in tension for easy observation of the cracks.[3] Histograms of the cracking density Λ (cracks/cm^2) as a function of crack length

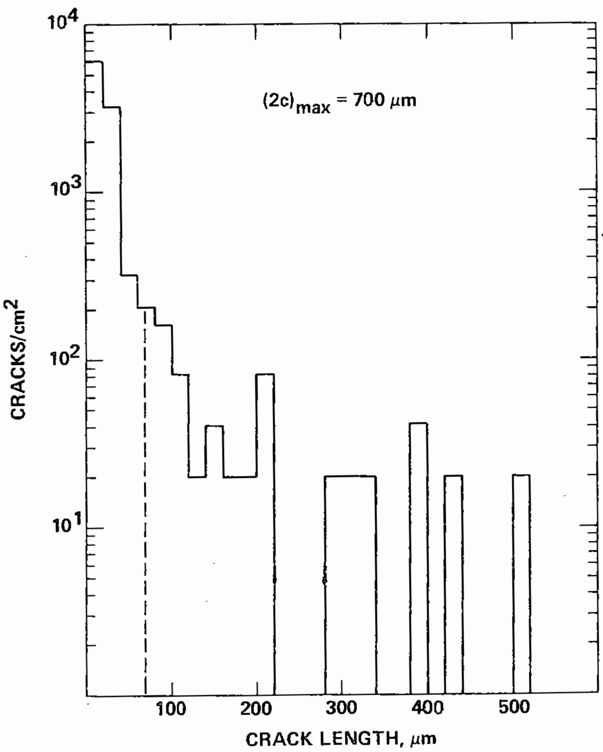

Fig. 2 Histogram of the cracking density as a function of crack length.

(2c) were then obtained, an example of which is shown in Fig. 2. Such histograms as a function of fatigue should contain all information necessary to determine the harmonic generation coefficient β. In the work reported here, detailed histograms have been taken only after termination of the harmonic generation experiments (100% of the fatigue life expended in the initiation phase). Histograms of the intermediate states have been obtained using a Monte Carlo simulation of microcrack development[8] for the particular microstructure of the aluminum alloy used. In all cases, the calculated histograms matched the experimental ones quite well. Since the Monte Carlo simulation[8] is based upon actual crack nucleation and early growth data on aluminum alloys, there is every reason to believe that this interpolation method reflects the actual microcrack development with sufficient accuracy, and, in the few cases studied so far, this speculation has been confirmed.

RESULTS

A. <u>Life Time Prediction in Initiation</u> - In the following, an attempt is made to relate the second harmonic generation data to microcracking parameters, a step necessary to arrive at a successful fatigue life prediction during the initiation phase of fatigue. To arrive at such a relation the assumption was made that harmonic generation occurs where the fracture surfaces contact each other gently. This area of contact is schematically shown in Fig. 3 as a dark

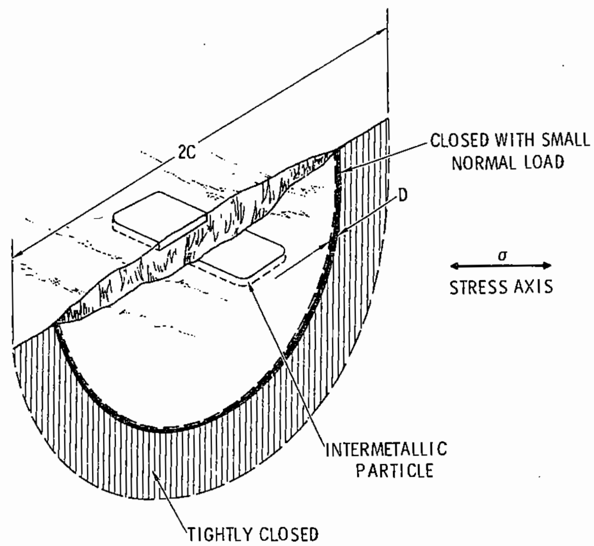

Fig. 3 Representation of a partially closed crack.

band. It is this region of low contact stress in which Richardson's analysis[4] would be qualitatively applicable. As an external tension or compression stress is applied, the crack will start to open or close. If the stress is high enough, harmonic generation will cease to occur for both tension and compression. Semi-quantitatively, the second harmonic amplitude generated per microcrack should then be proportional to the crack length (2c). For any length element in the path of the SAW of width d the microcrack density of Λ cracks per cm^2 will make an infinitesimal contribution to the harmonic generation given by

$$\Delta A_2 \propto \frac{d\Delta x}{F} \Sigma(2c) \tag{5}$$

In Eqn (5), $\Sigma(2c)$ is the total crack length interrogated by the SAW and F = $d\ell$ (ℓ = total path length). In the following the quantity $1/F\ \Sigma(2c)$ will be simply defined as $(2c\Lambda)$, where Λ may be interpreted as the cracking density. Therefore

$$\Delta A_2 \propto d(2c\Lambda)\Delta x. \tag{6}$$

Integration over the total path length (assuming that the attenuation is negligible) and combining Eqns. (4) and (6), yields

$$\beta \propto \frac{d(2c\Lambda)}{[A_1(0)]^n} \tag{7}$$

so that the relative change in harmonic generation (due to microcracks) is given by

$$A_2(\ell)-1 = kF(2c\Lambda), \tag{8}$$

where k is a proportionality constant. The quantity $F(2c\Lambda)$ may be interpreted as the total crack length, seen by the SAW, which can be obtained either by direct experimental observation or from the Monte Carlo simulation (which is based on experimental data as pointed out before). First results, obtained by a comparison of the harmonic generation data taken at $\sigma_{max} = 0.9\,\sigma_{yield}$ (see Fig. 1), with the total crack length, as obtained from a Monte Carlo simulation, verify the prediction of Eqn. (8) satisfactorily, as shown in Fig. 4.

In addition, the Monte Carlo simulation yields information about the relation of the quantity $(2c\Lambda)$ and the fraction of life spent in fatigue, N_i. The result, for the same specimen as previously discussed, is shown in Fig. 5 which can be expressed by the empirical relation

$$(2c\Lambda) = (2c\Lambda)_t \, N_i^2 \quad , \tag{9}$$

at least above about $N_i = 0.5$. In Eqn. (9) the quantity $(2c\Lambda)_t$ is primarily related to the total crack length at the point where 100% of the fatigue life in the initiation phase has been spent. Combining Eqns. (8) and (9) yields the remaining fatigue life

$$\Delta N_i = 1-N_i \tag{10}$$

to be

$$\Delta N_i = 1-\sqrt{\frac{A_2(\ell)-1}{kF(2c\Lambda)_t}} \tag{11}$$

From the Monte Carlo simulation a value $F(2c\Lambda)_t$ = 14.3 mm is obtained for the experimental conditions under discussion and from Fig. 4, $k = 0.245\ mm^{-1}$. Using the second harmonic data (at $\sigma_{max} = 0.9\sigma_{yield}$) from Fig. 1, thus yields a measured fraction of remaining fatigue life, $\Delta N_{measured}$, which can be compared with the actual fraction of remaining life in initiation, ΔN_{actual}. As shown in Fig. 6, ΔN_{actual} and $\Delta N_{measured}$ (using Eqn. 11) basically follow a one-to-one relationship to within 5% above about 50% of expended fatigue life. Below 50% of expended fatigue life, deviations seem to be mainly caused by the statistics of nucleation and early growth within the first grain. The above analysis appears to be applicable, however, as soon as the longest cracks overcome the first grain boundaries. Indications for this transition at 50% life expended become quite apparent by splitting the quantity $(2c\Lambda)$ into a part that contains all cracks smaller than D, the mean grain diameter, and a part that contains all cracks larger than D:

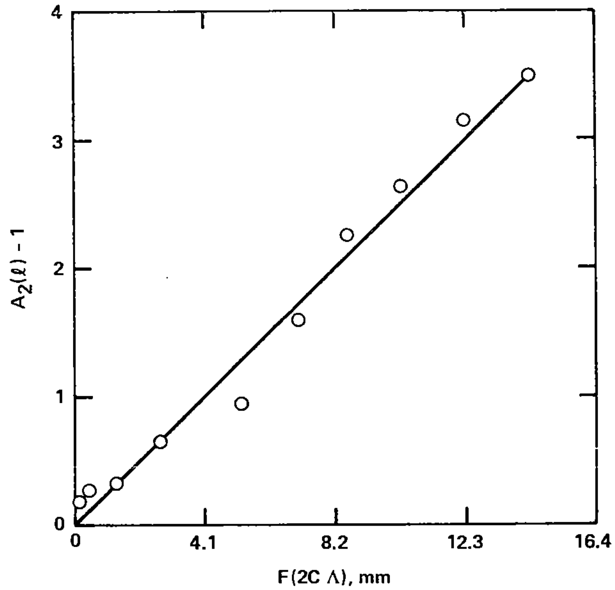

Fig. 4. Harmonic generation data as a function of total crack length $F(2c\Delta)$.

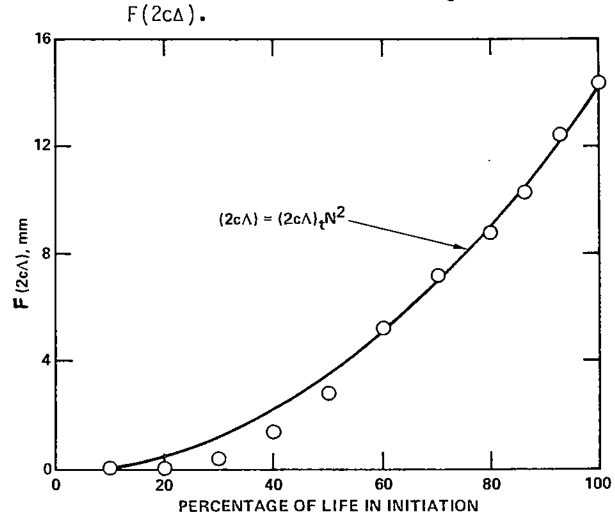

Fig. 5 The quantity $F(2c\Delta)$ as a function of life in initiation at $\sigma_{max} = 0.9\sigma_{yield}$

$$(2c\Lambda) = (2c\Lambda)_{2c<D} + (2c\Lambda)_{2c>D} \tag{12}$$

The result is shown in Fig. 7. After an initial growth, the quantity $(2c\Lambda)_{2c<D}$ stays about constant above 50% of life expended. At the same time $(2c\Lambda)_{2c>D}$ starts to grow rapidly. Based upon this separation it is possible to express the quantity $(2c\Lambda)_t$ in Eqn. (11) in the following way (without going into the details). For a material of mean grain size diameter D = 70 μm (as investigated in the present work) the longest crack, after 100% of life have been expended in initiation, has a size

$$(2c\Lambda)_t \approx 3.1\ D\Sigma_t \qquad (13)$$

(where Σ_t is the cracking density of all cracks that are larger than D),
and since, in the present case,

$$(2c)_t \approx 8D \qquad (14)$$

we obtain

$$(2c\Lambda)_t \approx 1/3\ (2c)_t\Sigma_t \qquad (15)$$

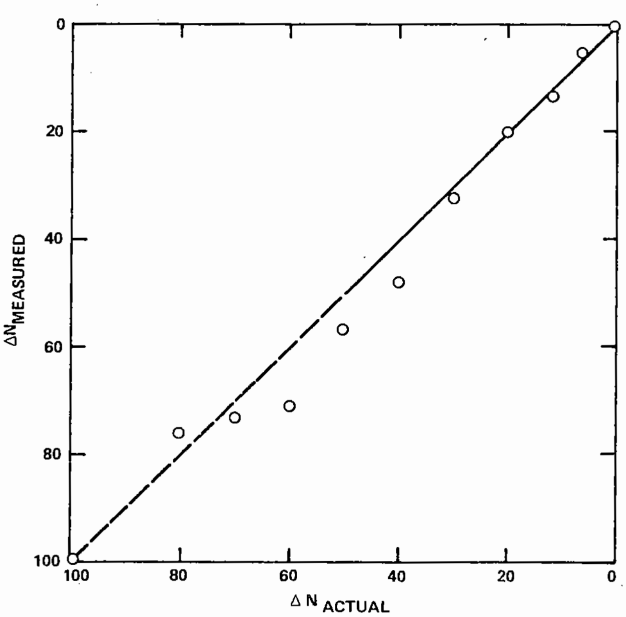

Fig. 6 Comparison of remaining fatigue life, $\Delta N_{measured}$, determined from harmonic generation data, versus ΔN_{actual}.

These quantities in Eqn. (15), as obtained from actual SEM and optical microscopy, are given in Table II for the three stress levels at which harmonic generation data have been obtained. These data show that Eqn. (15) holds reasonably well at the lower stress levels. Some deviation at $\sigma_{max} = 0.9\sigma_{yield}$ is caused by the fact that the largest cracks on this specimen started to grow predominantly at the specimen edges outside the region of microscopy. Indications are, however, that the quantity $(2c\Lambda)_t$, which is related to the total crack length (thus including all cracks, even the ones that are unimportant to failure) may be replaced by the product of length and density of the cracks, important to failure.

Even of more interest may be the last column in Table II. On all specimens, subjected to a wide range of fatigue stress levels, we find that the quantity $(2c\Lambda)_t$ is basically independent of σ_{max}. Since it is to be expected that the values for k and F in Eqn. (11) are also independent of σ_{max}, the harmonic generation should be independent of σ_{max}, a result which is basically observed, as evidenced by Fig. 1.

B. Life Time in the Propagation Phase - In order to confirm the previous statement, that for smooth bar specimens the major part of the total fatigue life is spent in initiation,

TABLE II

Cracking Parameters as a Function of Maximum Fatigue Stress Level

σ_{max}	$(2c)_t$ mm	Σ_t cm^{-2}	$(2c\Lambda)_t$ mm cm^{-2}
0.59 σ yield	0.75	341	95.7
0.76 σ yield	0.56	492	131.7
0.9 σ yield	0.40	175	90.7

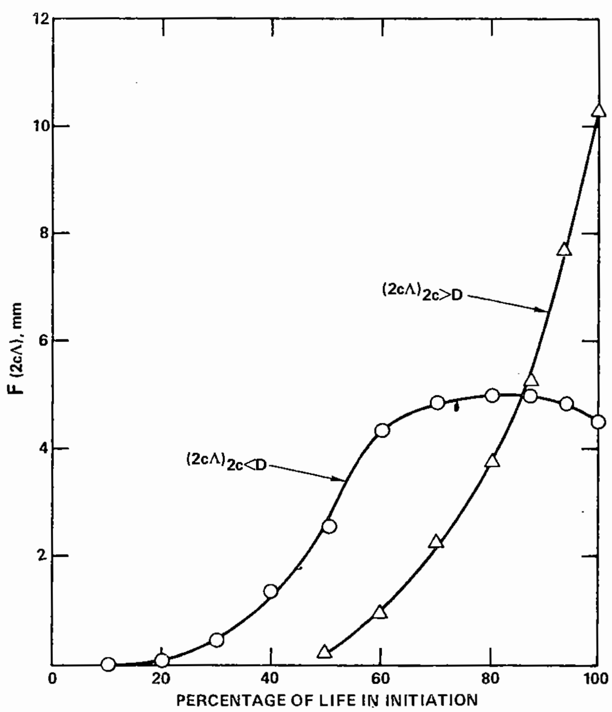

Fig. 7 The separation of the quantity F(2cΔ) into a part for which all cracks are smaller than D and a part for which all cracks are larger than D.

specimens that had been pre-fatigued in flexure were exposed subsequently to unidirectional tension - tension fatigue (thus avoiding the non-uniform through-the-thickness stress distribution experienced in flexure). After prefatigue, the tapered geometry of the specimen was changed to one of uniform cross section, to give the longest crack, which may be anywhere along the tapered section, a chance for further growth, leading to failure of the specimen.

Three specimens were prepared, as indicated in Table III. A first one was not exposed to pre-fatigue at all, a second one was pre-fatigued to $N_i \approx 0.65$ (1800 cycles) and a third one to N_i 1 (2700 cycles) at $\sigma_{max} = 0.9\ \sigma_{yield}$. As expected the second specimen contained cracks, the longest one having a size of the mean grain diameter. The longest crack of the third specimen had grown to a surprisingly large size (1400 μm).

For a lifetime prediction it is important to know the crack depth a. Certainly, the aspect ratio is smaller than the usual value of 0.5, which is the equilibrium value in a uniform stress field over the total cross section, since in flexure the stress goes to zero at the needed axis. We estimated, therefore, that the cracks grown in prefatigue may have an aspect ratio in the vicinity of 0.3, yielding the crack depth estimates given in Table III. Failure is assumed to occur as soon as the longest crack, achieved during prefatigue, reaches the backface of the specimen, thus yielding[9]

$$\Delta N_p = \frac{2}{(m-2)A(B\Delta\sigma)^m} \left\{ \frac{1}{a^{(m-2)/2}} \quad \frac{1}{d^{(m-2)/2}} \right\} \tag{16}$$

where m = 2.8, $A = 1.6 \times 10^{-8}$, B a geometrical factor[9] (chosen for a part-through crack), $\Delta\sigma$ = 350 MNm^{-2}, a the initial crack depth and d the specimen thickness (1.5 mm). As may be seen from Table III, the calculated ΔN_p for the third specimen is somewhat too high (by about a factor of 2.5). This overestimate is to be expected, since we used a (straight line) "Paris Equation" which does not account for the sigmoidal shape of the actual da/dN versus ΔK curve. Furthermore possible coalescence of the longest crack with other microcracks has not been taken into account. From this point of view, we have to consider the agreement between the calculated and observed ΔN_p as reasonable. Most important, however, is the observation that the remaining life of the third specimen, $\Delta N_{observed}$ 350 cycles, is indeed short with respect to the life in initiation. Comparing the data for the specimen fatigued at $\sigma_{max} = 0.76\ \sigma_{yield}$ (see Table I) with the ones above indicates that for fatigue at a comparable stress level only about 5% of the total life is spent in the propagation phase.

Table III also shows that the discrepancy between the calculated and observed ΔN becomes worse, the smaller the longest crack, and it is quite clear, that the simple minded fatigue life prediction becomes more and more inadequate. It is satisfying, however, that the observed ΔN_p becomes larger, the smaller the longest crack.

CONCLUSIONS

The presented work is an initial attempt to develop a life prediction methodolgy in the initiation phase of metal fatigue. This methodology is based upon the relation between microcrack development and the outputs of a nondestructive testing method, in the present case harmonic generation. It is clear that improvements are necessary, particularly in describing the functional relations of microcrack density and length of the longest crack on one hand and the remaining life in initiation on the other hand in a more appropriate statistical form, rather than in an empirical one. However, even in the present form, it seems possible, to take the microstructural parameters of the alloy investigated into full consideration. Further work is also needed to pinpoint the exact mechanism of harmonic generation at fatigue cracks, presently thought to be due to the opening and closing of the cracks.

However, we believe we have shown, that fatigue life prediction in metals is possible over the last 50% of the life spend in initiation, which is a vast improvement over present day technology. It is thus believed, that the developed methodology may be applicable to programs such as "Retirement for Cause" in which early fatigue crack detection is necessary.

ACKNOWLEDGMENT

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TABLE III.

Calculated at observed remaining life in tension-tension fatigue of prefatigued specimens.

Tension-Tension conditions: $\Delta\sigma = 350\ MN_m^{-2}$, $\sigma_{yield} = 500\ MN_m^{-2}$, $\frac{da}{dN}$ $1.6 \times 10^{-8}\ (\Delta K)^{2.8}$

Specimen	2c (μm) (Otpically)	a (μm) (Estimate)	ΔK Start ($MNm^{-3/2}$)	ΔN_p (Observed)	ΔN_p (Calculated)
No Prefatigue (N_i = 0)	0	0	0	6420	∞
1800 Cycles (N_i = 0.65)	70	20	3.3	3560	5.0×10^4
2700 Cycles (N_i = 1)	1400	400	11	350	890

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SUMMARY DISCUSSION
(Otto Buck)

Gordon Kino (Stanford University): Can you tell me why there is an N squared relation for the life prediction curve?

Otto Buck: You mean, why does ($2c\Lambda$) increase with N squared? No, I cannot at the present time.

Gordon Kino: It's empirical?

Otto Buck: Yes. It's empirical.

Alastair Morton (NSRDC): Did you look at any other methods of fatigue life prediction other than this one before you started? For example, any dislocation density measurements? Is there something in the literature that relates to degree of hardening due to dislocation density changes in the surface layers with the life?

Otto Buck: What we are looking at right now are residual stresses in the surface and the change of those with fatigue and you can see these effects using X-ray or acoustic techniques. In direct answer to your question, we have looked at dislocations in pure aluminum and there are indications that the acoustic harmonic generation changes due to a shakedown of the dislocation structure during fatigue, but I don't think that these are, at least in the high-strength aluminum alloys, overriding effects because of dislocation repinning. There are certain materials, high purity aluminum, e.g., where you can see slight effects on the attenuation, but these are very small. The major attenuation effect in the present case stems from generation of the microcracks. In general, I believe that in materials where immediate dislocation repinning is possible, you should be able to see dislocation rearrangements (fatigue hardening or softening). The only method that I know of, that is not hampered by this problem, is positron annihilation, because it does not require dislocation mobility. In addition, and if you are lucky, you may be able to use an eddy current method, but that may require low temperatures to see effects due to dislocation resistivity.

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